Three High Duty Cycle, Space-Qualified Mechanisms

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INTRODUCTION

The Michelson Doppler Imager (MDI) is a scientific instrument aboard the Solar and Heliospheric Observatory (SOHO) spacecraft. In 1995 the spacecraft will be put into a halo orbit about the L1 Lagrangian point (equal sun and earth gravity). The MDI looks at the sun continuously and takes a picture with a large format CCD camera every 3 seconds. The design goal of the mission is 6 years, so over 60 million pictures will be taken. The sun, being a high intensity source, provides a signal with a single pixel noise level of 0.2%. Many images are combined to measure the oscillatory motion of the sun so very high performance is required of the mechanisms in order that they not add noise to the data. The MDI instrument is made up of two parts, the electronics package and the optics package. Figure 1 shows the layout of the optics package. This paper describes the design and testing of three mechanisms on the MDI which are required to operate large numbers of times.

SHUTTER

The shutter precisely controls the exposure time of the CCD camera, and additionally selects either a magnified or an unmagnified beam path. Its design uses a brushless DC motor with an integral, optical, shaft angle encoder (figure 2). The motor is an Inland Motor RB-00502 unhoused brushless DC motor. The rotor is supported by a wave spring preloaded pair of ball bearings. The bearings are MPB part number SR3FCHH lubricated with BRAYCO 815Z. The motor drives a thin aluminum disk that contains a pie shaped opening of 80 degrees. The encoder provides the position feedback for commutating the motor, as well as the information required for measurement of the realized exposure at 9 locations across the image. Figure 3a shows exposures, measured by the encoder, as the shutter motor was being life tested. Each point represents a single 100 millisecond exposure taken after 20,000, 50 millisecond exposures. Figure 3b shows 500 consecutive exposures, and 3c is a histogram of 3b.

Shutter Characteristics:

Exposure	40 ms to 65 sec.
Uniformity	50 microseconds p-p.
Repeatability	80 microseconds p-p.
Absolute Exposure Accuracy	250 microseconds
Design Life	60 M Exposures
Power	15 V @ 150 mA peak
	5 V @ 80 mA peak
Weight	125 grams (motor and blade)

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A single exposure requires the shutter motor to make 3 moves. First the motor moves to start the exposure. After waiting in the open position for the desired exposure period the motor then closes the shutter. Because of the way the shutter is used to select the 1X or 3X path (see figure 1) a third move is needed. After the CCD camera reads out the image (this requires darkness and takes about 2 seconds) the shutter moves to where it can begin another exposure. Figure 4 shows a computer simulation of a 100 millisecond exposure. At time = 0 and position 200 degrees the motor is started in order to open the shutter. The motor operates open loop (BEMF limits the motor speed) until position 260 degrees (label B). At this time the windings are shorted and the motor comes to a stop at the 280 degree position. At time = 100 milliseconds (the desired exposure) the motor is started in order to close the shutter. The windings are shorted at 340 degrees and the motor comes to a final stop at the 360 degree position.

We compensate for the opening edge of the shutter moving through the field of view (A to B in the figures) by having the closing edge (C to D) move in exactly the same way with respect to the field of view. The non-uniformity resulting from the opening edge of the shutter moving across the field is thus canceled by the closing edge. Since the motor is a brushless DC motor there is some inherent torque ripple (one ripple per commutation step) that causes some speed variation even after the motor has reached its no-load speed. By placing the opening edge of the blade an integral number of commutation steps from the closing edge, the exposure non-uniformities caused by torque ripple during the opening move are canceled by the same torque ripple on the closing move.

The MDI shutter is very similar in design to the shutter used on the Soft X-ray Telescope (SXT) on the Yohkoh space mission. On the SXT shutter we minimized the effect of the magnetic detent on the exposures by selecting a motor with an odd number of stator teeth. The SXT shutter motor has 8 rotor magnets and 27 stator teeth, or 216 potential magnetic detent positions. The result of the small spacing of the detents is that under certain conditions small changes in voltage or bearing friction can cause the motor to stop in a different detent. Another difference between the MDI and SXT shutter is the SXT shutter has a single beam path and two openings in the blade, a 3 degree opening for 1 millisecond exposures, and a 60 degree opening for 20 milliseconds and longer.

For the MDI shutter we took a different approach. We selected a motor with 6 rotor magnets and 18 stator teeth. This causes a total of 18 magnetic detents, 1 detent for each commutation step. Since the motor is designed to stop in the center of a magnetic detent it can be off by as much as +/- 10 degrees without falling into the next detent. We take advantage of the even spacing of the magnetic detents to insure that the opening and closing edges of the shutter blade always start from the same position.

MICHELSON TUNING MOTORS

The Michelson tuning motor assembly (figure 5) is used to tune the passband of the Michelson interferometers by rotating 1/2 wave retarders. The assembly consists of 2 brushless DC motors in a single housing. The motors were designed and built for MDI by H.Magnetics. The motors have hollow rotors to which the waveplates are directly attached, and incremental encoders for position feedback.

Tuning Motor Characteristics:

Repeatability	+/- 1 arc min.
Design Life	60 M moves
Step Size	2 degrees
Power Dissipation	50 mJ / 24 deg move (dissipated at the motors)
Power	15 V @ 100 mA peak
	5 V @ 80 mA peak
Weight	590 grams (2 motors)

An unusual feature of the tuning motors is that each motor contains a single thin-section ball bearing. The bearing is an MPB part number S2936 thin section ball bearing. A preload force is applied by offsetting the rotor axially from the stator. This preloads the bearing because the magnets try to pull the rotor into the stator. The preload force was measured to be approximately 18 N (4 lbs). In order to verify that the tuning motor met the positioning requirements of MDI a test was done where a small mirror was glued to the center of the waveplate. By observing the mirror through a theodolite we verified that the motor could be positioned repeatably to well within the specification over a wide range of motor voltages.

FILTERWHEELS

The MDI contains three wheels, each of whose purpose is to place one of four optical elements into the beam path. The polarization analyzer wheel selects the polarization of light which enters the MDI in order to measure the magnetic field of the sun. The other two wheels comprise the calibration/focus system, which has two purposes. First they provide calibration of the MDI optical system by placing a pair of lenses into the optical path. In addition they enable one to adjust focus on-orbit by inserting flat glass elements of different thicknesses into the beam path. Each wheel consists of a brushless DC motor with an integral, optical, incremental encoder. The motors have hollow rotors within which reside the optical elements. The rotors are supported by wave spring preloaded pairs of ball bearings. The bearings are MPB part number SR4FCHH lubricated with BRAYCO 815Z. The motors were also designed and built by H.Magnetics for MDI. Figure 6 shows the filterwheel assembly.

Filterwheel Characteristics:

Repeatability	+/- 1 arc min.
Design Life	2 M moves
Step Size	2.5 degrees
Power	15 V @ 100 mA peak
	5 V @ 80 mA peak
Weight	420 grams

COMPUTER SIMULATIONS

Prior to building the motors, computer simulations were run for each of these mechanisms. These simulations were very helpful in the proper sizing of the motors and in the selection of their windings. In addition they provided disturbance torque data to the spacecraft designers.

The simulations were done in IDL (Interactive Data Language). The technique is to take a large number of small time steps. The motor windings are modeled as a series resistor and inductor. The motor current is calculated by subtracting the BEMF from the motor supply voltage, and applying it to the resistor and inductor. Torque ripple is modeled with the BEMF "constant" actually being a function of rotor position. Magnetic detent is assumed to be a sinusoidal function of rotor position. To initiate the simulation the motor is stopped, voltage is applied, current increases through the resistor and inductor, current causes torque, and torque causes speed and position to change. Speed causes BEMF which is subtracted from the applied voltage for the next time step. Figure 7 shows the output of this program as well as an actual oscilloscope measurement of the motor current. Figure 8 shows the IDL program which was used to model the tuning motors.

CONTROL SYSTEMS

The control systems for all three types of mechanisms are very similar. The Michelson tuning motors and the wheel mechanisms use identical electronics, a block diagram of which is shown in figure 9. The control system of the shutter is similar except that it incorporates a programmable timer to control the exposure, and does not have the ability to stop the motor at an arbitrary position.

To move a filterwheel or tuning motor the Dedicated Experiment Processor (DEP) first loads the desired stopping position into a latch in the motor drive electronics. Then the DEP tells the motor to run in either the clockwise or counterclockwise direction. The motor runs until the programmed stopping position is reached, plus a small time delay. The windings are then shorted together and the motor's energy is dissipated in the windings as the motor brakes to as stop. After another delay the encoder is shut off to conserve power while the motors are not being used. Very little power is therefore consumed by these mechanisms when they are not moving. The first delay is adjusted so that the motor comes to a stop exactly in the center of the next detent. The second delay insures that the motor is completely stopped before the encoder is shut off.

The method of operating the motors open-loop and making use of the magnetic detent for position accuracy allowed for a simple control system. This method of controlling the motors has proved itself to be robust, as the motors continued to function acceptabaly throughout their life tests even though in some cases the bearings had deterierated considerably. This can be attributed to selecting (or designing) motors with adequate torque margins.

LIFE-TESTING

These mechanisms have all undergone extensive life-testing in a vacuum chamber. Prior to placing the mechanisms in the vacuum chamber they were subjected to a vibration test. Pressure in the vacuum chamber during the life tests varied from about 10^{-6} to 10^{-7} Torr. The shutter and wheel mechanisms were at room temperature, and the tuning motors were in a temperature controlled oven at 35 C. This simulates the environment in which the mechanisms will actually be used. A PC clone controlled the mechanisms through prototype versions of their flight control electronics. The PC also controlled test equipment over an IEEE-488 bus, enabling the life-test to be automated. Each mechanism was alternately cycled through 20,000 operations, and then characterized by running at 5 different voltages while recording the current and speed at each voltage.

The design goal of the shutter and tuning motor mechanisms is 60 million operations each since these mechanisms will be used once every 3 seconds for 6 years. In order that the life tests of these mechanisms be completed in a reasonable time it was necessary to accelerate the tests. This was done by running the motors at their design speeds, and on the same voltage they will run on in flight, but spending very little time between moves. The shutter test was done with a 50 millisecond exposure time, long enough to insure that the motor comes to a complete stop but much shorter than the planned exposures. The tuning motor tests were made with one motor making 30 degree moves and the other 60 degrees. This is how they will be used in the instrument. The test acceleration was done by reducing the time the motors spent stopped between moves. In this way we were able to make approximately 4 moves per second on each motor, rather than a move every 3 seconds.

The shutter and wheel mechanisms both used ball bearings lubricated with BRAYCO 815Z. The shutter life test put the equivalant of 67 million exposures on the motor. The friction during the test (figure 10) was essentially constant. Examination of the bearings after the test showed them to be in perfect condition. The filterwheel test showed a gradual trend of increasing friction and of increasing variation of friction (figure 11). The test was considered a success because the design life of the filterwheel is 2 million operations. The filterwheel continued to function perfectly throughout the test. Examination of the bearings after this very excessive over test showed them to be in poor condition.

The Michelson tuning motor has had three sets of bearings installed for three different life tests. The first tuning motor test used Teflon toroids and was lubricated with BRAYCO 815Z oil. Figures 12a and 12d show the friction vs. time for the two motors. Each point represents a motor characterization done after 20,000 moves. After 34 million moves the friction of one of the motors was increasing at an unsatisfactory rate and the test was stopped. The Teflon separators showed considerable wear.

This first tuning motor test used a constant power heater to attempt to keep the temperature at 35 C. Closed loop heater control was added for the second and third tests. An improved method of measuring current was also included in the second and third tests. The reduction of the scatter in the calculated friction for the second and third tests can be attributed to these improvements in the test setup.

The second tuning motor test (figures 12b and 12e) used separators made of SALOX-M, a mixture of Teflon and bronze, and was also lubricated with BRAYCO 815Z. This second test was stopped when one of the motors again exhibited rapidly increasing friction. Examination of the bearings showed a lack of lubrication and a considerable amount of wear particles, especially in the bearing whose motor showed increasing friction.

The third test (figures 12c and 12f) used bearings with SALOX-M separators lubricated with BRAYCOTE 600 grease. This test lasted 7 months, put 66 million moves on one motor and 102 million on the other, and was stopped after a 6 year equivalent mission life was reached. Visual examination of the bearings showed them to be in fine condition. BRAYCOTE 600 grease lubricated bearings are being used in the flight tuning motors.

CONCLUSION

The requirements on these flight mechanisms (tens of millions of cycles, performance stability, minimal disturbance torque, and low power consumption) led to custom designed, high pole-count, permanent magnet motors in conjunction with a unique control approach. The filterwheel and tuning motors designs were a cooperative and iterative effort by Lockheed Palo Alto Research Laboratories (LPARL) and H.Magnetics. LPARL designed the housings, encoders, and control electronics, while H.Magnetics designed the rotors and stators in accordance with LPARL requirements. An extensive, in-vacuum test program was conducted and in the case of the tuning motors design changes (lubrication) were required, as was retesting. At this time the mechanisms described in this paper have been fully qualified and are about to be installed into the flight MDI. They are also planned for use in a new solar payload.

ACKNOWLEDGMENTS

The MDI is a scientific experiment being developed by the Stanford Lockheed Institute for Astrophysics and Space Research. Phil Scherrer, of Stanford University, is the Principal Investigator, and Alan Title is the program leader at the Lockheed Palo Alto Research Laboratory where these efforts were conducted. Chris Edwards is acknowledged for his assistance with the electronics, and Mike Levay for his computer expertise. The SOI-MDI program is supported by NASA contract NAS5-30386. The CIP and SXT programs were supported by contracts NAS5-26813 and NAS8-37334.

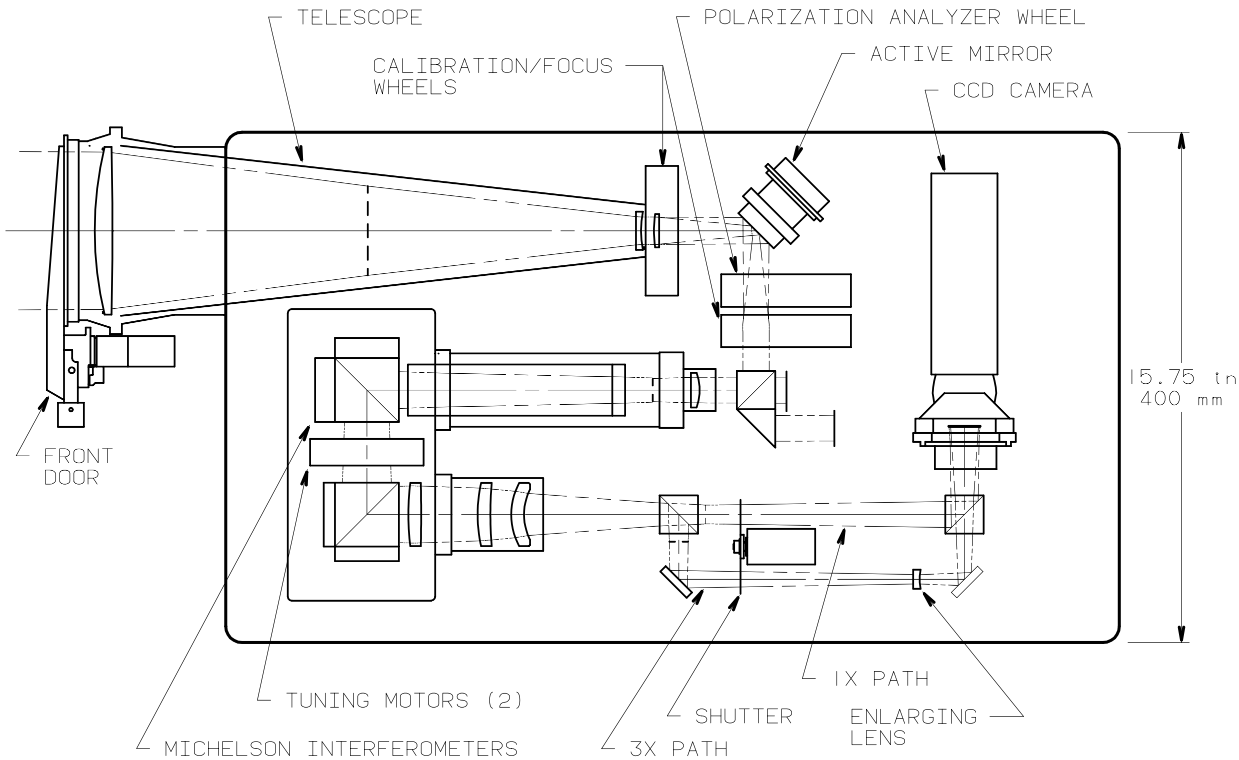

Figure 1. MDI Optics Package Layout

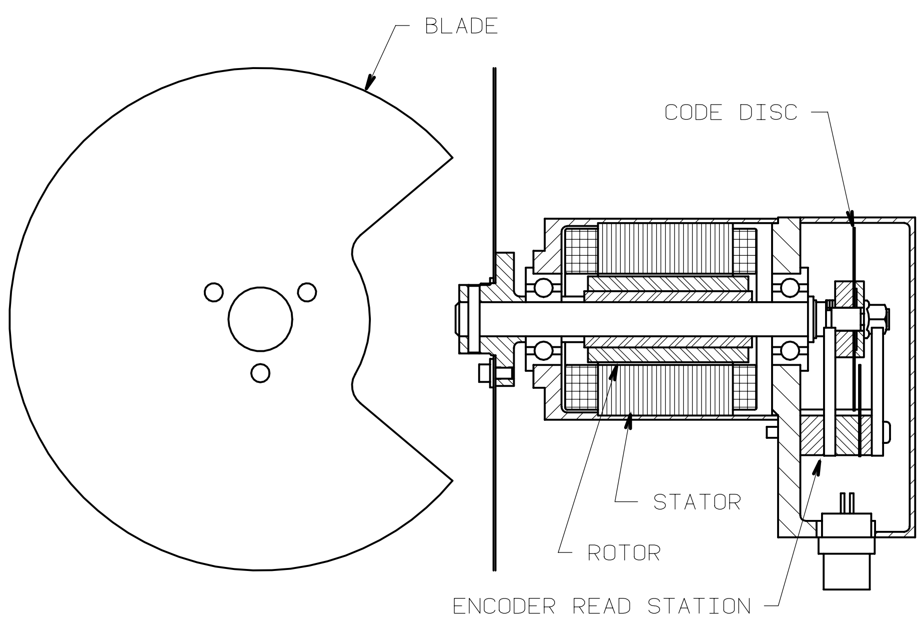

Figure 2. Shutter

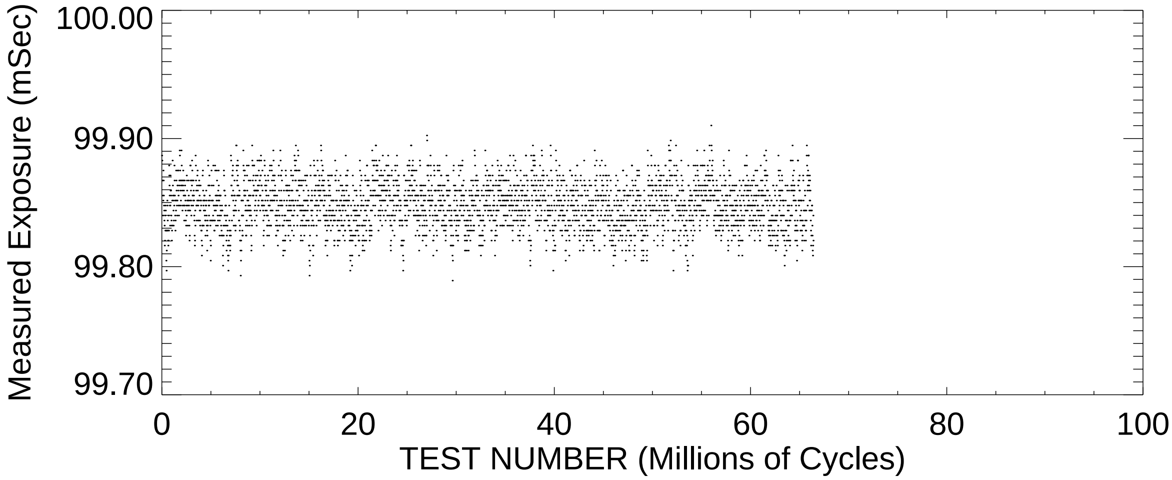

Figure 3a. MDI Life Test Shutter (each point is after 20,000 exposures)

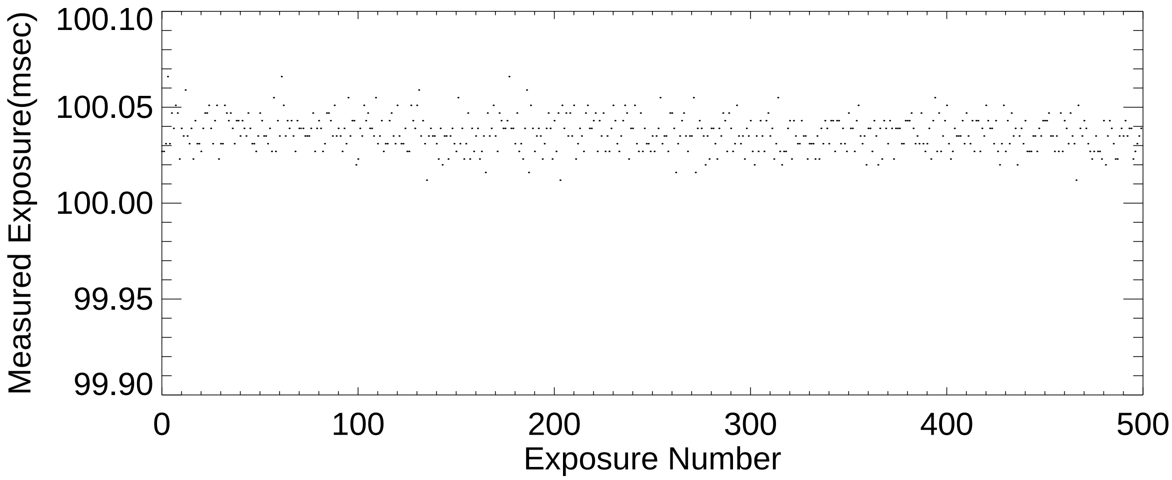

Figure 3b. 500 Consecutive Exposures, MDI Flight Shutter

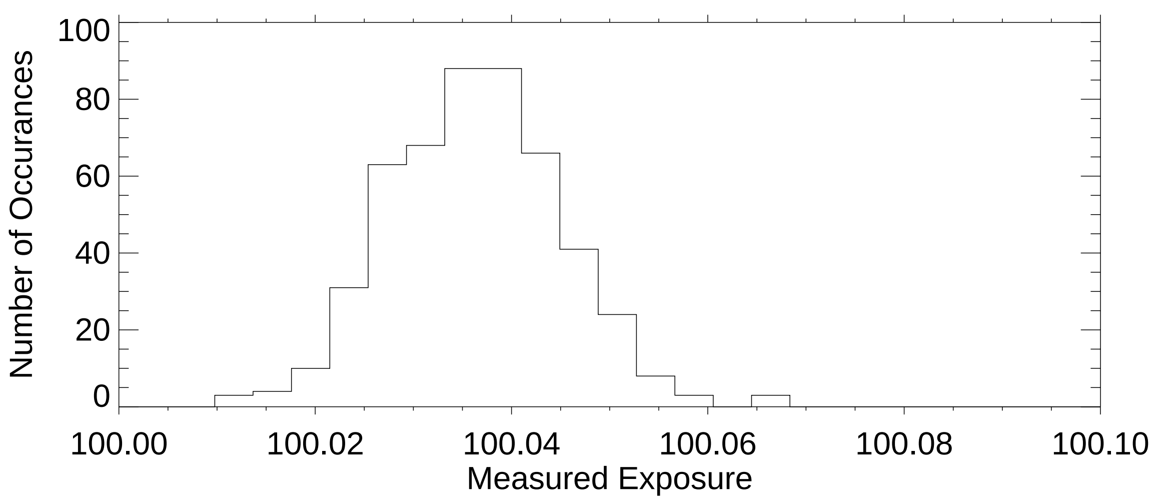

Figure 3c. Histogram of Figure 3b

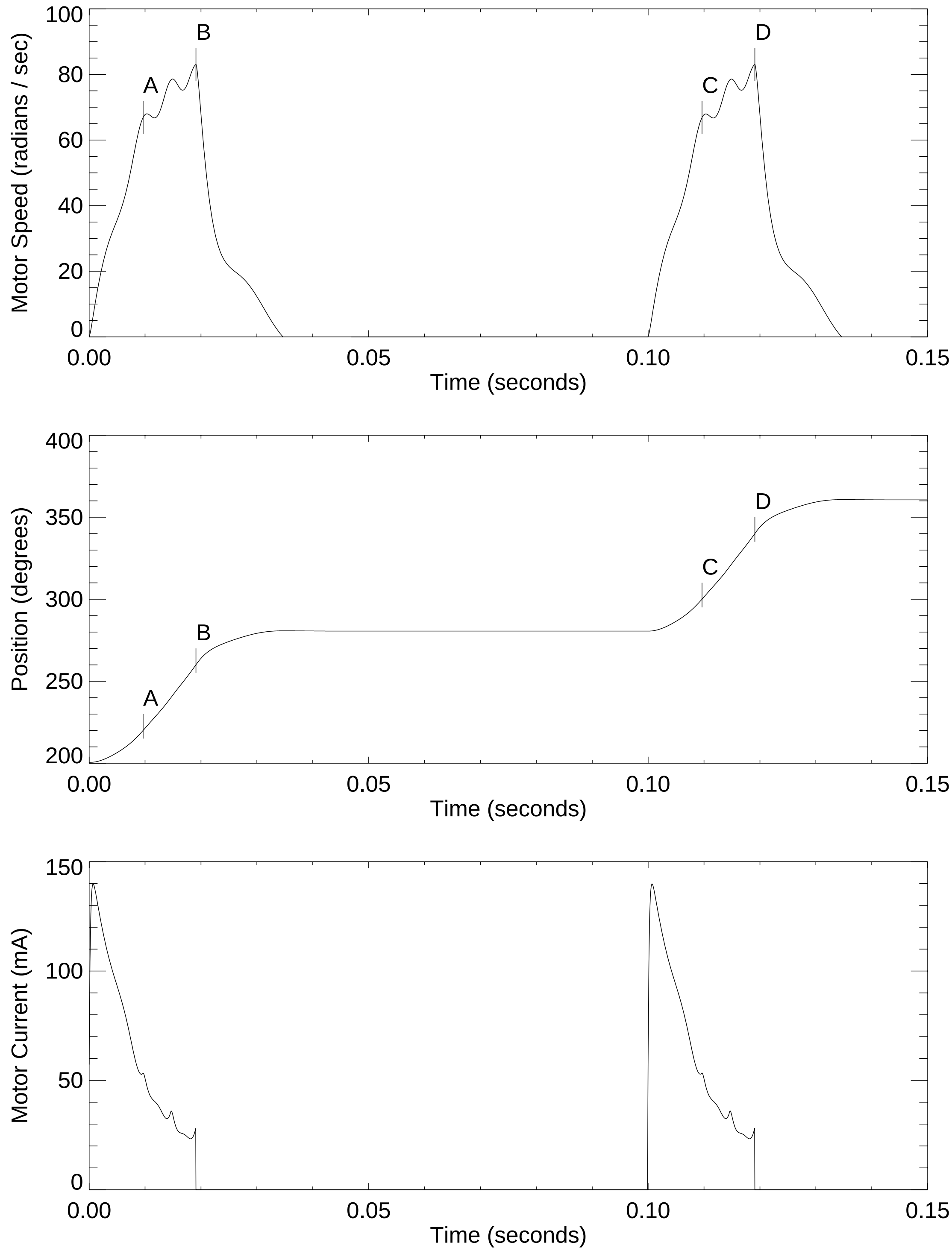

Figure 4. Computer Simulation of 100 millisecond Exposure

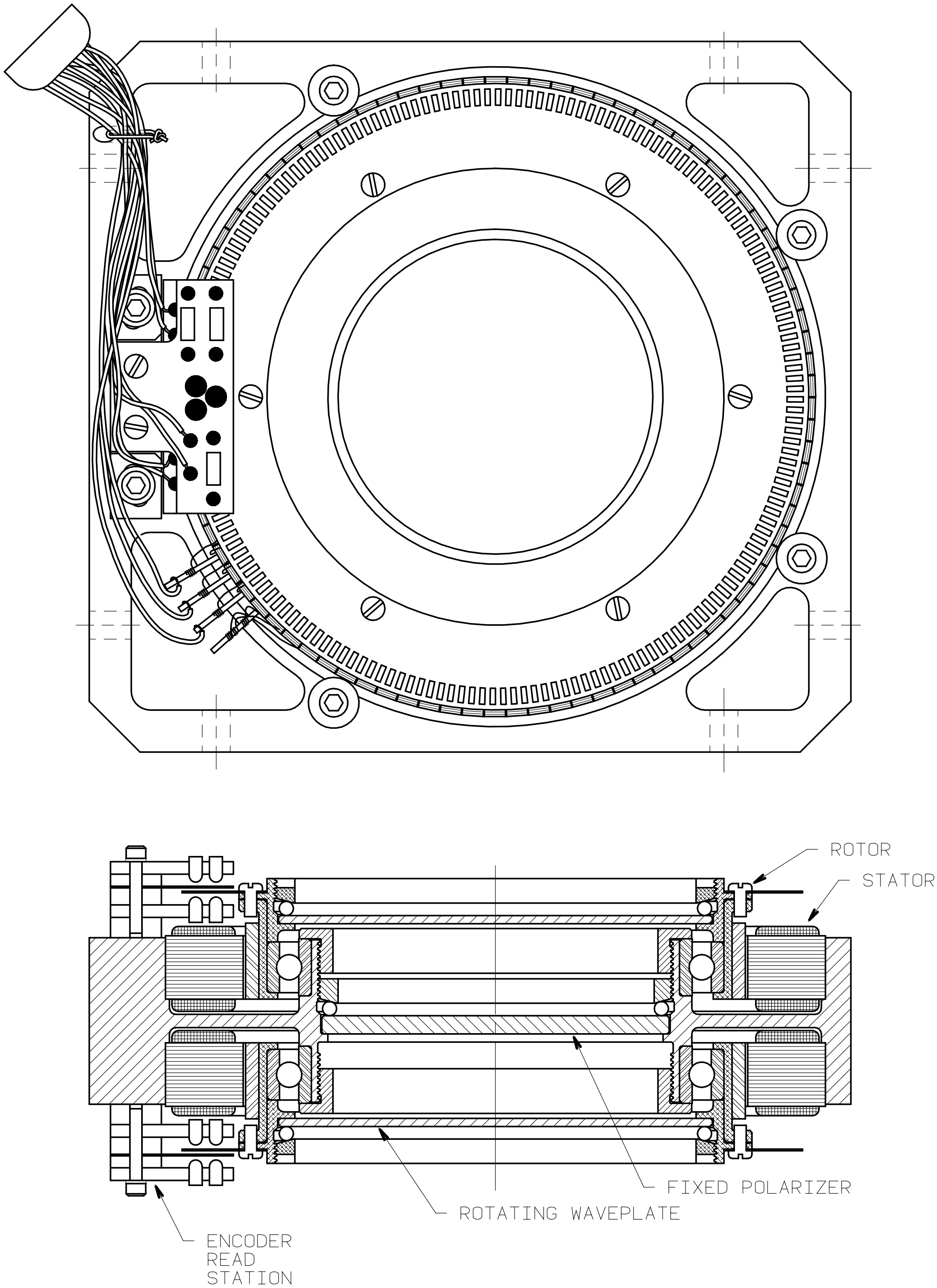

Figure 5. Michelson Tuning Motor Assembly

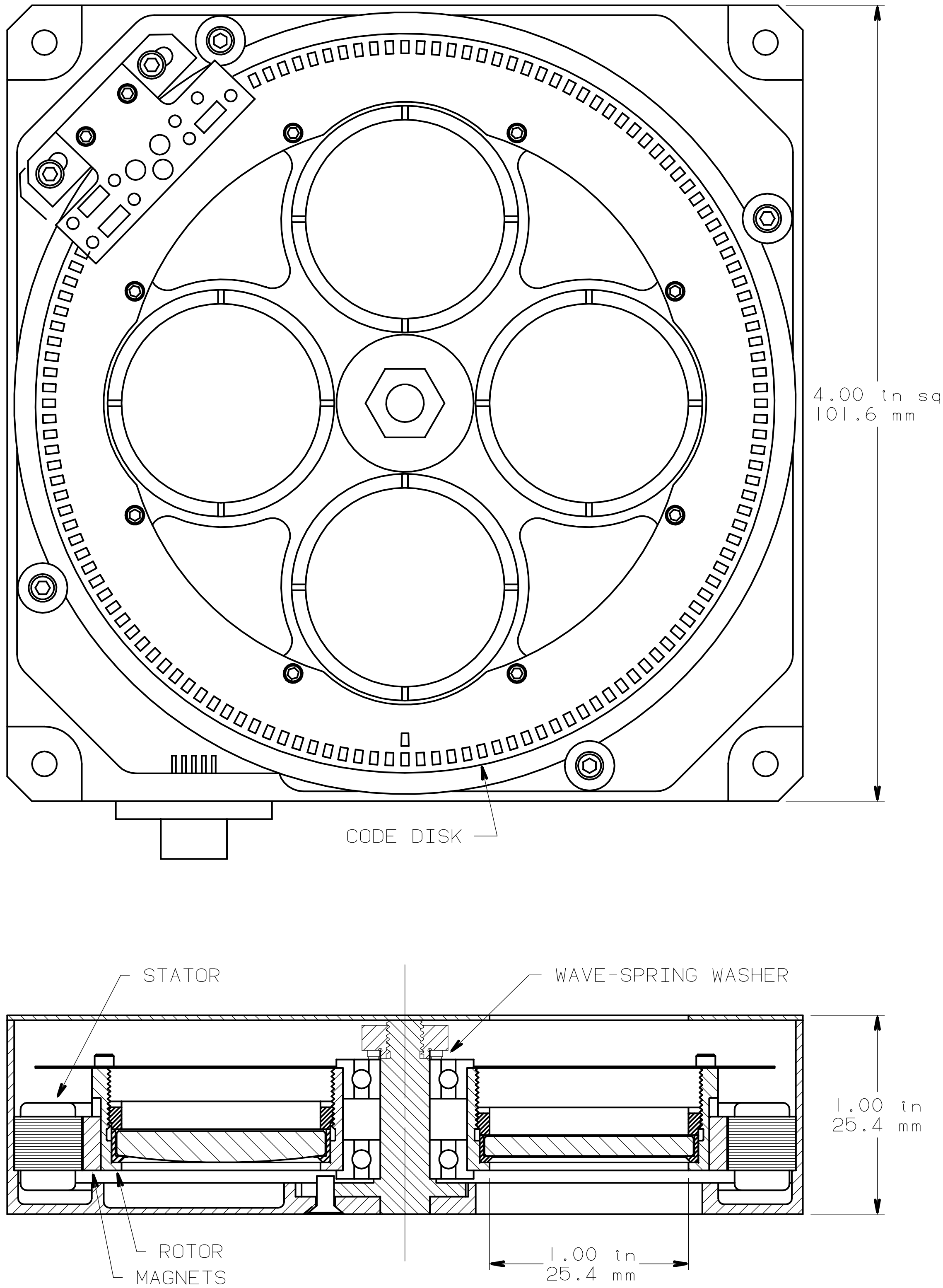

Figure 6. Filterwheel Assembly

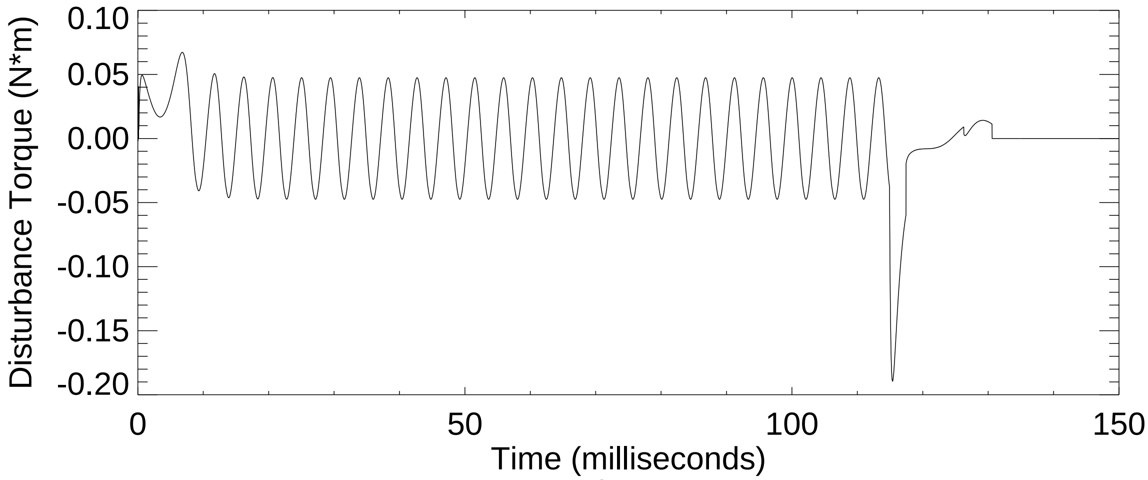

Figure 7a. Computer Simulation of 50 Degree Tuning Motor Move

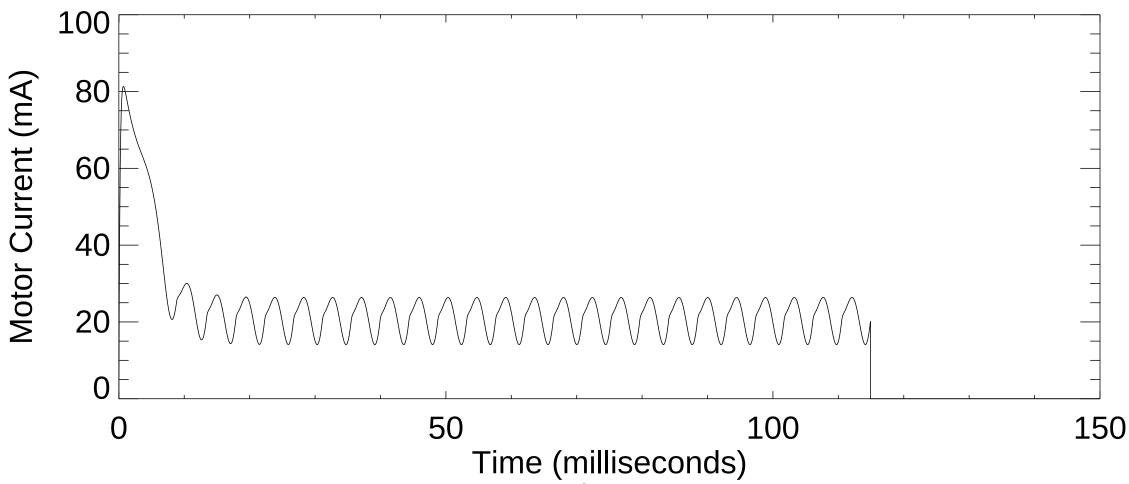

Figure 7b. Computer Simulation of 50 Degree Tuning Motor Move

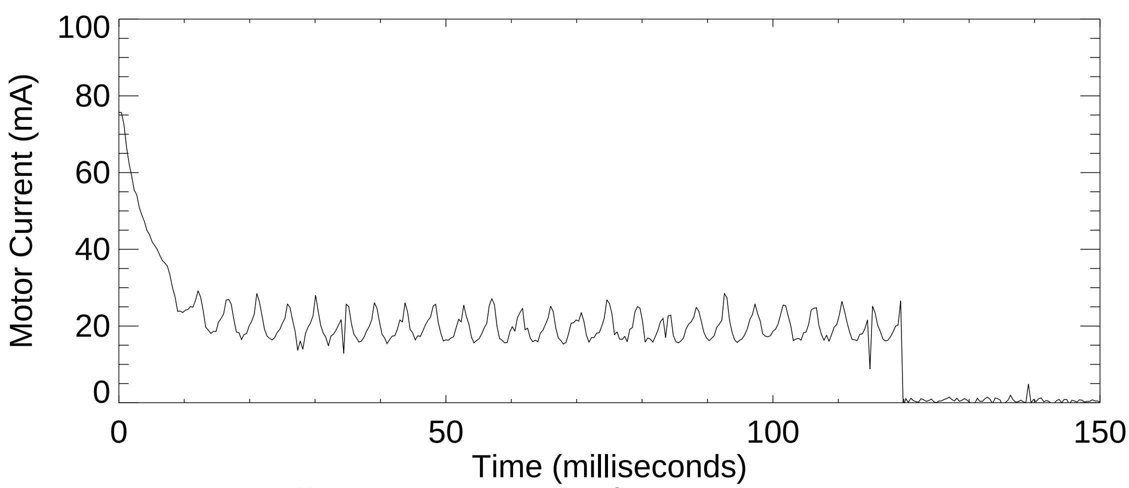

Figure 7c. Oscilloscope Measurement of 50 Degree Tuning Motor Move

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RANGE = .10                                     ; plot range
DT = .00002                                     ;time step
NUM = RANGE/DT                                  ;number of time steps
KP = 1.48                                       ;V / rad/sec
J = .0052                                       ;inertia (oz-in sec**2)
R = 172                                         ;resistance
VO = 15.4                                       ;motor voltage
L = .032                                        ;inductance (Henries)
NPP = 30                                        ;number of pole pairs
DF = .17                                        ;viscous damping (oz-in / rad/sec)
TD = 5.0                                        ;detent torque (oz-in)
STOPD = 50                                      ;stopping position (degrees)
STOP = STOPD/57.2958                            ;stopping position (radians)
HDRAG = 2.8                                     ;drag torque (oz-in)
A=FLTARR(NUM,6)

FOR I=1,NUM-1 DO BEGIN
A(I,0) = A(I-1,0) + DT                          ;ime
A(I,1) = A(I-1,1) + DT*A(I-1,5) / J             ;omega (rad/sec)
IF (A(I,1)GE 0.) AND (A(I-1,1)LE 0.) AND (ABS(TORK)LE HDRAG) THEN A(I,1)=0.
IF (A(I,1)LE 0.) AND (A(I-1,1)GE 0.) AND (ABS(TORK)LE HDRAG) THEN A(I,1)=0.
A(I,2) = A(I-1,2) + DT*A(I,1)                   ;theta (rad)
IF A(I,2) GT STOP THEN VO=0.
THETAE = A(I,2)*NPP                             ;theta-electrical
K = KP*SIN((THETAE MOD 1.0472) + 1.0472)        ;torque ripple
IF A(I,2) GT STOP THEN K=KP*1.155               ;stopping K
A(I,3) = (VO - A(I-1,4)*R - K*A(I,1)) / L       ;dI/dt
A(I,4) = A(I-1,4) + DT*A(I,3)                   ;current
IF A(I,1) GT 0. THEN DRAG = HDRAG ELSE DRAG = -HDRAG
TORK = K*141.6*A(I,4) - DF*A(I,1) - TD*SIN(6*THETAE+.75)
A(I,5) = TORK - DRAG                            ;torque
IF (A(I,1)GE 0.) AND (A(I-1,1)LE 0.) AND (ABS(TORK)LE HDRAG) THEN A(I,5)=0.
IF (A(I,1)LE 0.) AND (A(I-1,1)GE 0.) AND (ABS(TORK)LE HDRAG) THEN A(I,5)=0.
ENDFOR
Z=0                                             ;I=0 after stop
FOR I=1,NUM-1 DO BEGIN
IF A(I,2) GT STOP THEN Z=1
IF Z EQ 1 THEN A(I,4)=0
ENDFOR

SET_PLOT,'PS'
DEVICE,/PORTRAIT,/INCHES,YOFFSET=.5,YSIZE=10.,XSIZE=7.
!P.FONT=0
!P.POSITION=[.12,.8,.85,1]
!Y.TITLE="Motor Current (mA)"
!X.TITLE="Time (milliseconds)"
PLOT,A(*,0)*1000,A(*,4)*1000
!Y.TITLE="Disturbance Torque (N*m)"
PLOT,A(*,0)*1000,A(*,5)/141.6                   ;convert torque from oz in. to Nm

END
```

Figure 8. IDL Program for Brushless DC Motor Simulation

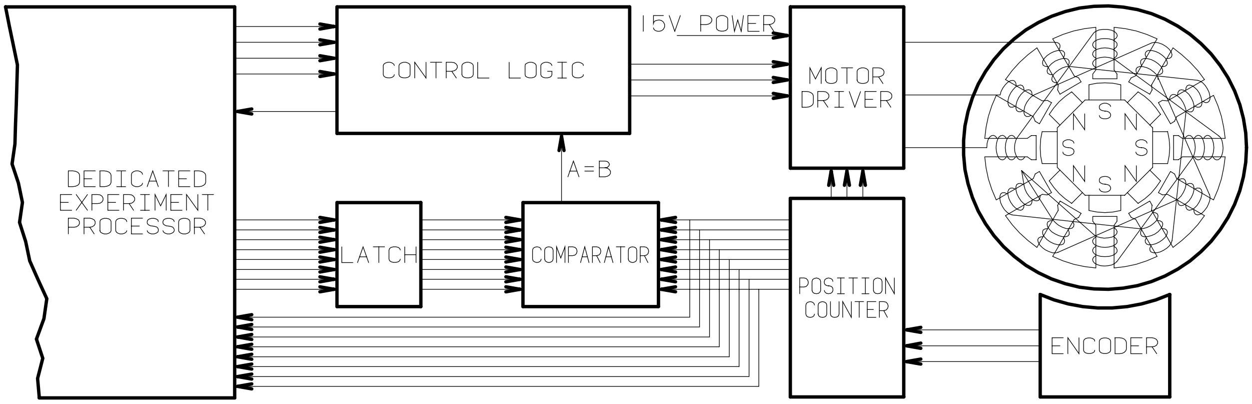

Figure 9. Filterwheel and Tuning Motor Control System Block Diagram

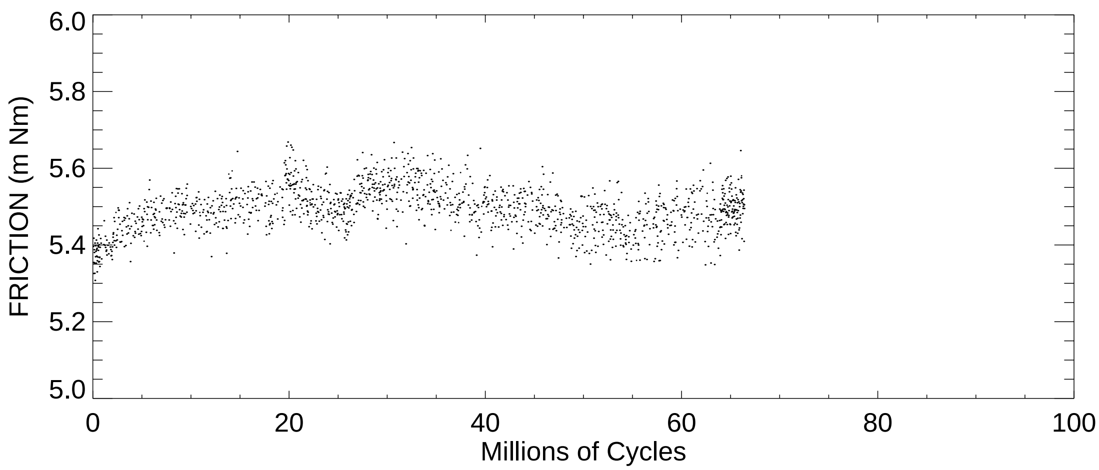

Figure 10. Shutter Life Test

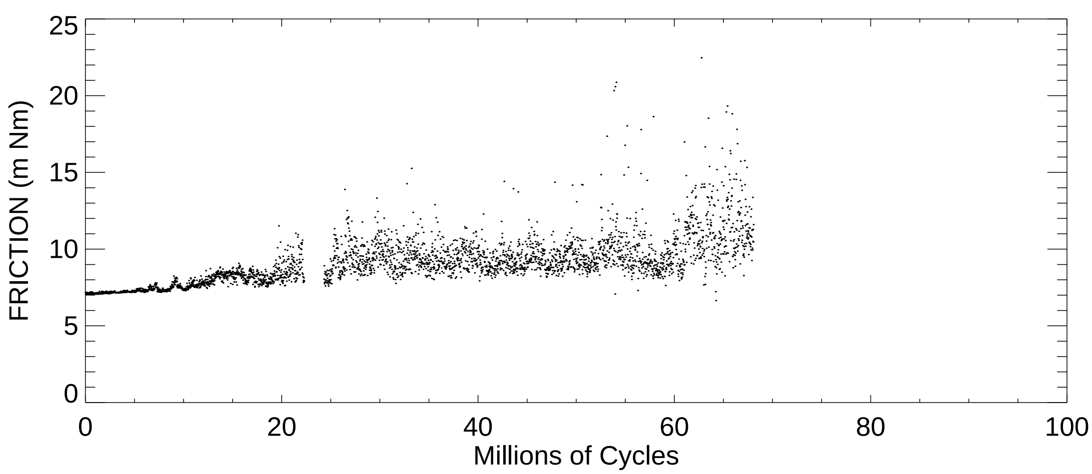

Figure 11. Filterwheel Life Test

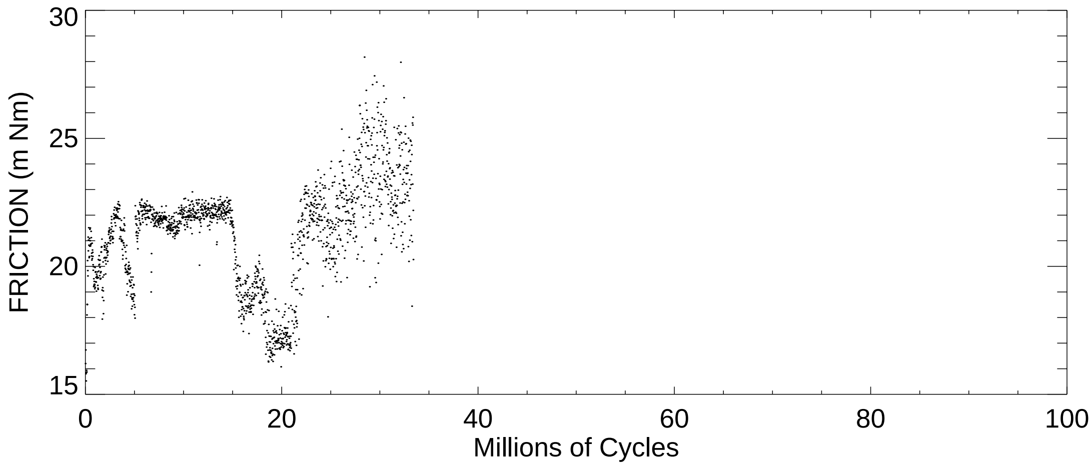

Figure 12a. Tuning Motor Test #1
Teflon toroid separators, 60 degree move, BRAY 815Z lubrication

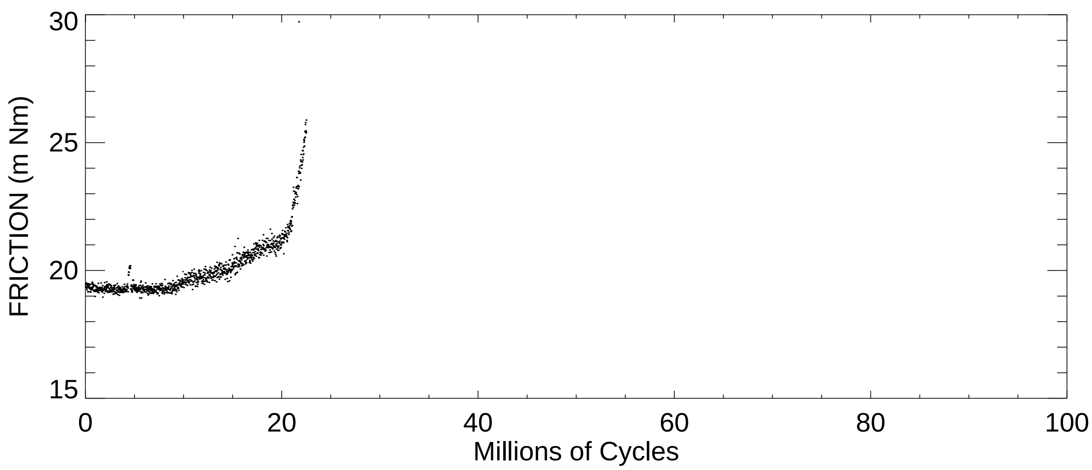

Figure 12b. Tuning Motor Test #2
SALOX separators, 60 degree move, BRAY 815Z lubrication

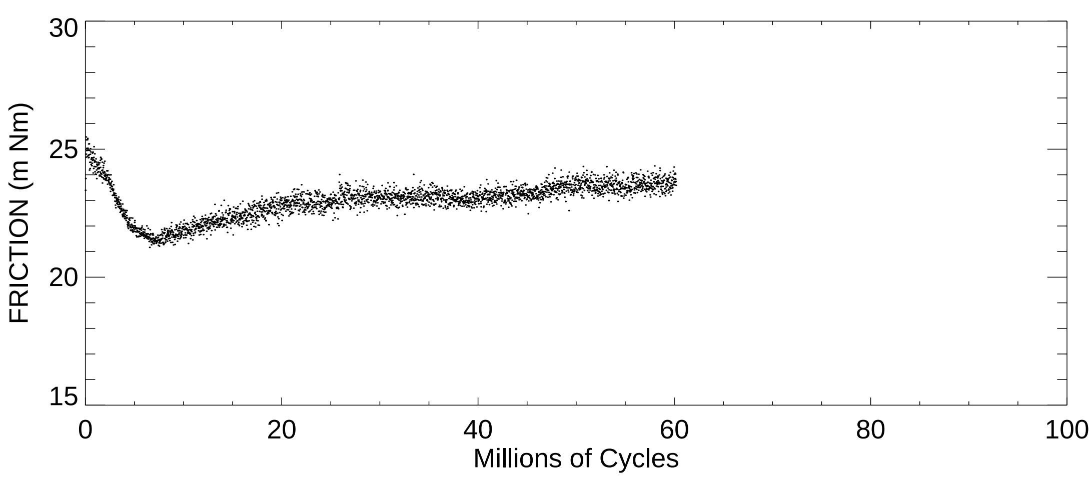

Figure 12c. Tuning Motor Test #3
SALOX separators, 60 degree move, BRAYCOTE 600 lubrication

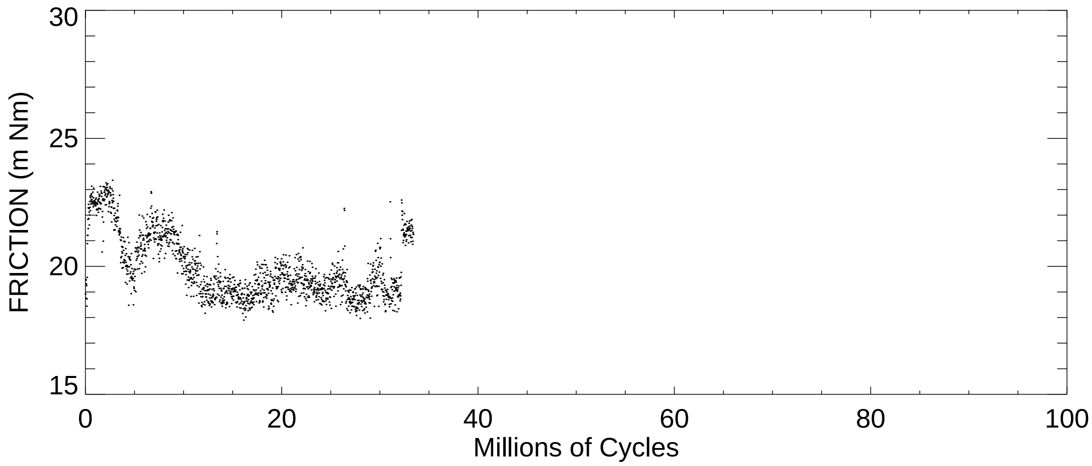

Figure 12d. Tuning Motor Test #1
Teflon toroid separators, 30 degree move, BRAY 815Z lubrication

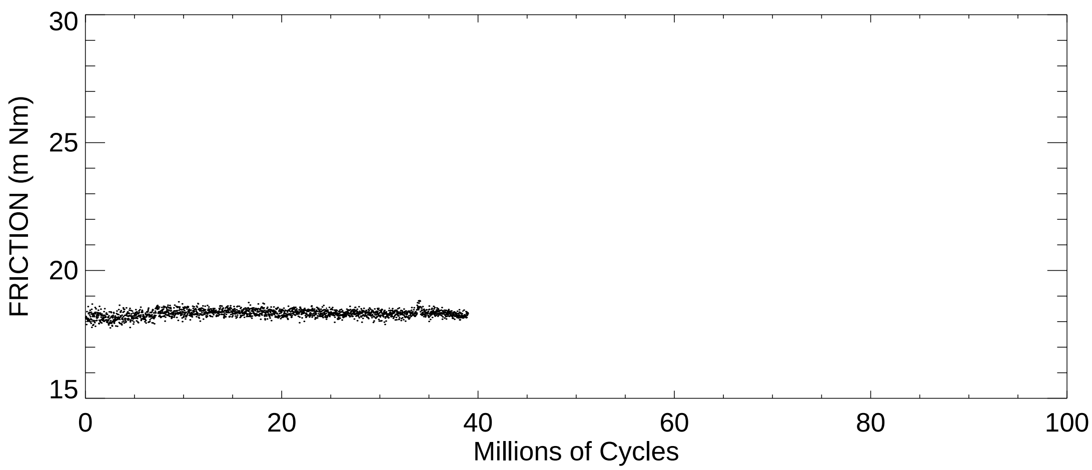

Figure 12e. Tuning Motor Test #2
SALOX separators, 30 degree move, BRAY 815Z lubrication

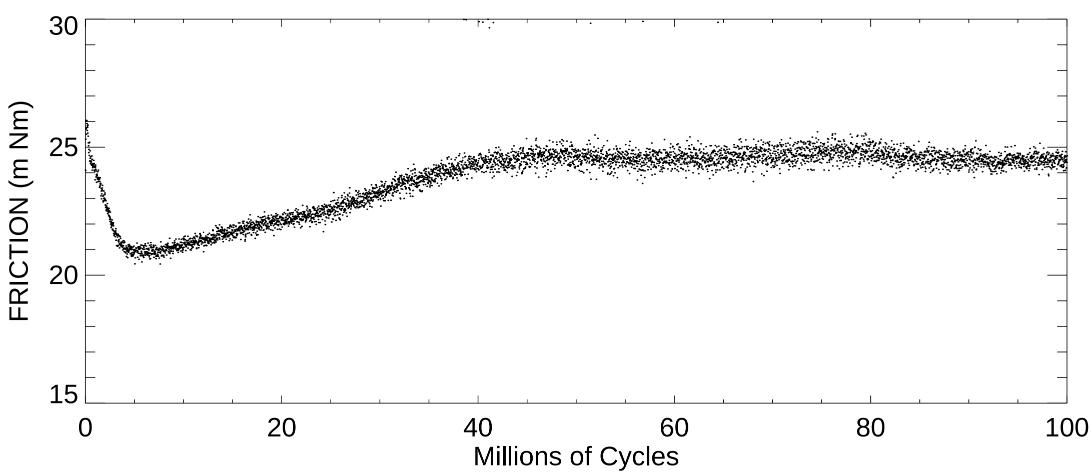

Figure 12f. Tuning Motor Test #3
SALOX separators, 30 degree move, BRAYCOTE 600 lubrication